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# CHEMICAL TRANSFER PROPULSION

# PROGRAM PLAN

Prepared by:

Robert L. Zurawski 11/28/88

Robert L. Zurawski
Program Manager,
Chemical Transfer Propulsion

Date

Approved by:

Gregory M. Reck
Director,
Propulsion, Power & Energy Division

Date

Approved by:

John C. Mankins
Program Manager,
Pathfinder

Date

OAST

Office of Aeronautics and
Space Technology

# FOREWORD

Pathfinder is a research and technology initiative by the National Aeronautics and Space Administration (NASA) which will strengthen the technology base of the United States civil space program and provide options for potential future space exploration missions. These missions may include an intensive study of the Earth, a return to the Moon, piloted missions to Mars, or the continuing robotic exploration of the Solar System. Pathfinder begins in fiscal year 1989, managed by the NASA Office of Aeronautics and Space Technology, to advance a collection of critical technologies for these missions and ensure technology readiness for future national decisions regarding exploration of the Solar System. Pathfinder extends the technological foundation being established by the Civil Space Technology Initiative (CSTI), which began in fiscal year 1989. While CSTI focuses on advancing a family of technologies for transportation to and operations in near Earth orbit and supporting science activities, Pathfinder looks toward longer-term missions beyond Earth orbit and into the Solar System.

Four major thrusts of Pathfinder are Surface Exploration technology, In-Space Operations technology, Humans-in-Space technology and Space Transfer technology. The Space Transfer thrust will provide the critical technologies needed for transportation to, and return from, the Moon, Mars, and other planets in the Solar System, as well as for reliable and cost-effective Earth-orbit operations. A key element of this thrust is the Chemical Transfer Propulsion Program which will provide the propulsion technology for high performance, liquid oxygen/liquid hydrogen engines to enhance or enable a variety of future space exploration missions.

This Program Plan describes the goals and objectives, management plan, technical approach, resources and financial management plan, facilities plan and technology transfer planning for the Chemical Transfer Propulsion element of Pathfinder. For additional information on the Chemical Transfer Propulsion Program, please contact;

NASA Office of Aeronautics and Space Technology,
Propulsion, Power and Energy Division,
Washington, D.C. 20546
Phone Number: (202) 453-2847

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# SECTION 1.0

# EXECUTIVE SUMMARY

## 1.1 PROGRAM GOALS AND OBJECTIVES

The goal of the Chemical Transfer Propulsion Program is to provide the technology necessary to confidently proceed, in the 1990's, with the development of high performance liquid oxygen/liquid hydrogen expander cycle engines for future space exploration missions. Such advanced chemical rocket engines would enable transportation to, and return from, the Moon, Mars, and other planets in the Solar System, as well as reliable and cost-effective Earth-orbit operations.

Major program objectives are to validate a design and analysis technology base and to demonstrate component and systems technologies for advanced liquid oxygen/liquid hydrogen expander cycle engines. This will involve validation testing of engine components, testing of these components assembled into an engine system (to study component interactions, system transients, system dynamics and health monitoring/control systems) and the application of experimental data to verify analytical design models/codes at both the engine component and engine system level. Key technical issues which will be addressed in the program include; high performance engine operation, reusability, deep throttling with minimum performance loss and design criteria for operation and maintenance of the engine in space.

The Chemical Transfer Propulsion Program is divided into three major research areas (Propulsion Studies, Mission-Focused Technologies and Engine Systems Technology) to allow work to be focused in critical areas and to provide a flow mechanism for raising the technology to higher levels of hardware definition, leading to the eventual testing of an advanced liquid oxygen/liquid hydrogen expander cycle engine system in a focused technology test bed in the late 1990's.

## 1.2 ORGANIZATION AND MANAGEMENT

A Program Manager in the OAST Propulsion, Power and Energy Division, Code RP, will have program management responsibilities for the Chemical Transfer Propulsion Program which include; 1) program planning to establish objectives, scope and overall programmatic approaches, 2) coordination with the Office of Exploration, the Office of Space Flight and organizations external to OAST to assure that future space vehicle requirements guide propulsion technology efforts within the program and 3) reporting on a regular basis to a Program Manager for Pathfinder as to program status and accomplishments. This Program Plan prepared by the Program Manager will furnish top-level programmatic information and serve as a "contract" between Code RP and OAST senior management as to the resource and institutional requirements to achieve the goals and objectives of the Chemical Transfer Propulsion Program. The OAST SSTAC advisory committee structure and advisory mechanisms will be utilized to provide top-level guidance to the program. A Space Propulsion Advisory Committee may also be formed to provide a more specific and dedicated advisory function to the program.

The NASA Lewis Research Center (LeRC) will be the Lead Center for the Chemical Transfer Propulsion Program and is the only Participating Center in the program at this time. A Project Manager at LeRC will be exclusively responsible for the execution of the program. The Project Manager will provide regular (monthly letters, quarterly MICS and an annual report), integrated assessments of the program to the OAST Chemical Transfer Propulsion Program Manager who will, in turn, report to the Pathfinder Program Manager. The Project Manager will develop a detailed Project Plan for the Chemical Transfer Propulsion Program. When approved by Headquarters annually, the Project Plan will serve as the "contract" between LeRC and OAST as to those efforts and resources required to fulfill the stated objectives of the program. Regular reviews will be conducted to ensure a planned pace of accomplishment to meet the goals and objectives of the program.

## 1.3 SCHEDULE AND DELIVERABLES

By the end of 1992, propulsion studies will be complete, generating engine parametric data and propulsion requirements to guide technology efforts in the program. Technology concepts for mission-focused technology efforts will be formulated and characterization of advanced designs and analytical methods will be accomplished using laboratory and bench rig tests. Breadboard engine efforts leading to the validation of the high pressure, high performance LOX/hydrogen expander engine concept will be well underway. Testing of components for the breadboard engines will be nearly complete leading to validation of engine component design methodologies and analytical models.

By 1998 all critical technologies for an advanced LOX/hydrogen expander cycle engine will be developed and verified in a focused technology test bed. Test bed engine testing in a simulated space environment will validate a system design/analysis technology base and design concepts for a high performance, space-based, throttleable, reusable LOX/hydrogen expander cycle engine, including definition of health monitoring and control systems and design criteria for operation and maintenance of the engine in space. By 1998, the technology necessary to confidently proceed with the development of an advanced LOX/hydrogen expander cycle engine for future space exploration missions will be available.

## 1.4 RESOURCES

Projected resources of $76 million are required to accomplish the milestones and to provide the deliverables on the specified schedule for the Chemical Transfer Propulsion Program for fiscal years 1989 through 1993. Resources approved and allocated for fiscal year 1989 total $4.0 million. Funding and workforce requirement for the first five years of the program are summarized in Table V.

# SECTION 2.0

# INTRODUCTION

## 2.1 PROJECT PATHFINDER OVERVIEW

American leadership on the space frontier requires aggressive programs in technology development. Technological advance will be critical to programs for future space exploration missions (Ref. 1). These missions may include an intensive study of the Earth, a return to the Moon, piloted missions to Mars, or the continuing robotic exploration of the Solar System (Ref. 2). The technologies needed for success in these ventures are many and varied. The National Aeronautics and Space Administration (NASA), recognizing that it must intensify and broaden the scope of its research and technology program to provide the range of technical options and elevate technological readiness in select areas to enable future space exploration missions, is initiating Project Pathfinder.

Project Pathfinder is a research and technology initiative which will strengthen the technology base of the United States Civil Space Program in preparation for future space exploration missions. Pathfinder is a long term program of both research and demonstrations which begins in fiscal year 1989, managed by the NASA Office of Aeronautics and Space Technology (OAST), to advance a collection of critical technologies for these missions and ensure technology readiness for future national decisions regarding exploration of the Solar System (Ref. 3).

Pathfinder is organized into four programmatic thrusts; (1) Surface Exploration (2) In-Space Operations (3) Humans-in-Space and (4) Space Transfer, as shown in Figure 1. The Surface Exploration thrust will provide the critical technologies needed for gathering scientific and engineering data for robotic and piloted missions to the Moon, Mars and other planets in the Solar System. Technologies needed for Earth-orbit staging and operations, as well as planetary operations will be worked in the In-Space Operations thrust. The Humans-in-Space thrust will provide technology and understanding needed to ensure safe and productive human space exploration missions. Finally, the Space Transfer thrust will provide critical technology for transportation to, and return from, the Moon, Mars and other planets in the Solar System, as well as for reliable and cost-effective Earth-orbit operations (Ref. 4). Additional information on Project Pathfinder may be found in the Pathfinder Program Plan (Ref. 5).

Chemical Transfer Propulsion is a key element of the Space Transfer thrust and will provide the technology for high-performance, liquid oxygen/liquid hydrogen expander cycle engines for space-based transfer vehicles, as well as for Lunar and Mars landers.

## 2.2 DOCUMENT PURPOSE AND SCOPE

The purpose of this Program Plan relative to the Chemical Transfer Propulsion Program is to;

(1) establish broad goals and objectives
(2) specify a top-level work breakdown structure
(3) define a management plan (including management structure, Center roles and responsibilities, individual roles, responsibilities and accountability, program planning, reporting and reviews)
(4) establish resource allocation and associated schedules, milestones and deliverables
(5) present a top-level technical plan
(6) present long-range Chemical Transfer Propulsion Program plans (technical, management, resource, facilities, and technology transfer)

The Program Plan furnishes top-level guidance and information on the scope, content and long-range plans of the Chemical Transfer Propulsion Program. A Project Plan prepared by the Lead Center of the program will detail the program. Collectively, the Program Plan and Project Plan will serve as implementation documents for the Chemical Transfer Propulsion Program, which begins in fiscal year 1989.

## SECTION 3.0

## CHEMICAL TRANSFER PROPULSION OVERVIEW

### 3.1 MISSION STUDIES AND TECHNOLOGY REQUIREMENTS

In a report to NASA in 1987, the Committee on Advanced Space Technology of the National Research Council recommended that advanced propulsion technologies for future space missions be afforded the highest priority of R&D activity within NASA (Ref. 6). Recognizing that propulsion is a pacing item for future space exploration missions, the committee suggested that NASA pursue a strong program leading to the design and development of reusable cryogenic transfer vehicle engines with features of fault tolerance, high reliability and longevity. The NASA Office of Aeronautics and Space Technology has responded with the Chemical Transfer Propulsion element of Pathfinder, which will provide the technology necessary to confidently proceed with the development of high performance LOX/hydrogen expander cycle engines for future space exploration missions.

NASA's planning for future exploration of the Solar System includes unmanned (precursor) and manned missions to Mars and its Moons, as well as a resumption of manned missions to the Moon to establish Lunar observatories. A significant portion of the cost for these missions depends on launch vehicle and on-orbit fuel requirements. One of the keys to reducing cost is to minimize the propellant mass in low-Earth orbit required to achieve a transfer trajectory to accomplish orbit insertion, to effect a planetary landing and to return to Earth. Launch of the many millions of pounds required for virtually all future space exploration mission scenarios may be affordable only if advanced propulsion systems can be made available (Ref. 6). Reduced propellant requirements in orbit translate to substantial cost savings because fewer Earth-to-orbit vehicle launches are required to accomplish the mission. For example, in the case of a manned Mars mission, an increase of 35 seconds of engine specific impulse may save the cost of at least two Earth-to-orbit vehicle launches. A key enabling technology to greatly reduce in-orbit propellant mass requirements is the development and use of high-performance chemical transfer engines.

Another key to reduced cost is to develop and utilize reusable transfer stages that are based in and operated from low-Earth orbit. Technologies that will enable automated in-orbit operation (such as refueling, maintenance, servicing and preflight systems checkout, as well as fault-tolerant in-flight operation) are critical to the successful development and use of space-based vehicle systems. Integrated controls and health monitoring systems will be required for such fault tolerant engines which will be repeatedly operated and maintained in space.

The NASA Office of Exploration (OEXP) is currently studying several mission scenarios to provide recommendations and alternatives for an early 1990's national decision on a focused program for human exploration of the Solar System. These mission scenarios include human expeditions to the Martian moon Phobos, human expeditions to Mars, human tended Lunar observatories and an evolutionary expansion from a Lunar outpost to Mars exploration (Ref. 7). Preliminary propulsion technology requirements generated by OEXP for these mission scenarios are presented in Table I. Additional technology requirements common to all propulsion systems include; (1) high reliability and fault tolerance (2) long life, space maintainable systems (3) restart capability (4) check out for reuse and (5) diagnostic capability (integrated controls and health monitoring).

## 3.2 TECHNOLOGY ASSESSMENT

The only upper stage LOX/hydrogen engine currently in operation is the RL-10 expander cycle engine which was developed and certified in the late 1950's and early 1960's. Two RL-10A-3-3A engines are used on the expendable Atlas Centaur vehicle. The RL-10A-3-3A is a regeneratively cooled, turbopump-fed rocket engine that weighs approximately 310 pounds and produces a rated vacuum thrust of 16,500 pounds (Ref. 8). This low pressure (465 psia) engine delivers moderate performance (444.4 seconds specific impulse at a mixture ratio of 5:1 using a 61:1 area ratio nozzle)*, has limited throttling capability (with significant performance penalties) and no on-board diagnostics, as shown in Table II. It was designed for and has been used only on expendable vehicles and is not compatible with future demands for performance, reusability, man rating, fault tolerant in-space operation and in-space maintenance.

In the early 1970's NASA initiated a technology program directed toward an advanced LOX/hydrogen upper stage engine, as shown in Figure 2. The program initially focused on an advanced space engine utilizing a staged combustion cycle for very high pressure, high performance operation. The Advanced Space Engine Technology Program was carried

* Later investments in RL-10 technology resulted in modest performance improvements (459.8 seconds specific impulse for the RL-10 Derivative IIB at a mixture ratio of 6.0 using a 205:1 area ratio nozzle).

through component verification testing, at which time it was decided that a LOX/hydrogen expander cycle engine would better satisfy future mission requirements. The Orbital Transfer Rocket Engine Technology Program, which began in the early 1980's focused on advanced component technologies for high performance (high pressure), reusable LOX/hydrogen expander cycle engines which would be space based and man rated. Efforts focused on technologies for high speed turbomachinery, high heat transfer combustors, large area ratio nozzles and health monitoring systems to address these longer term technology goals. The basic proof-of-concept of advanced, high-performance LOX/hydrogen expander cycle components was the aim of this program. Some limited testing of turbomachinery and health monitoring components in a breadboard engine and design studies for a flight version (RS-44) of this breadboard were also conducted.

What remains to be accomplished in order to confidently proceed with the development of an advanced high performance LOX/hydrogen expander cycle engine for future space exploration missions is the validation testing of engine components, testing of these components assembled into an engine system (to study component interactions, system transients, system dynamics and health monitoring/control systems) and the verification of analytical design models/codes at both the engine component and engine system level. Pathfinder Chemical Transfer Propulsion is a focused program intended to elevate technology readiness (to Level 6 as shown in Table III) to bridge the technology gap between basic research and technology efforts conducted to date (Level 3 of technology readiness) and the eventual development of advanced LOX/hydrogen engines for future space exploration missions.

## 3.3 CHEMICAL TRANSFER PROPULSION GOALS AND OBJECTIVES

The goal of the Chemical Transfer Propulsion Program is to provide the technology necessary to confidently proceed, in the 1990's, with the development of high performance liquid oxygen/liquid hydrogen expander cycle engines for future space exploration missions. Major program objectives are;

(1) The validation of a design and analysis technology base to support the development of future, high performance LOX/hydrogen expander cycle engines including;
   (a) Assembly and validation of analytical methodologies for the design of advanced LOX/hydrogen expander cycle engine components and systems
   (b) Validation of design concepts for high performance,

space-based, throttleable LOX/hydrogen expander cycle engines

(2) To demonstrate component and systems technologies for high performance, space-based, throttleable LOX/hydrogen expander cycle engines including;
   (a) Validation of high pressure, high performance expander cycle engine concepts
   (b) Investigation of engine system interactions, transients, dynamics, control functions and preliminary health monitoring techniques
   (c) Testing of advanced engine components, control systems and health monitoring/diagnostic systems

## 3.4 TECHNICAL APPROACH

At the present time, future space exploration mission scenarios have not been defined to a point where firm propulsion requirements exist. However, technology goals for an advanced LOX/hydrogen space engine which support the range of future mission options are presented in Table II. The major technical issues for an advanced LOX/hydrogen expander cycle engine to be addressed in the Chemical Transfer Propulsion Program are;

(1) High performance:
    High pressure engine operation (Goal of 490 lbf-sec/lbm vacuum specific impulse with 1000:1 area ratio nozzle)
(2) Deep throttling:
    Continuous and stable engine operation from rated thrust to 5% (20:1 vacuum thrust throttling ratio) with minimum performance loss
(3) Reusability/Life:
    Operational life greater than 500 starts/20 hours
(4) Design criteria;
   (a) In-space operation:
       Highly reliable, fault tolerant engine operation with diagnostic (integrated controls and health monitoring) instrumentation
   (b) In-space maintenance:
       Modular design for changeout in a space environment

The technical approach to be used in the Chemical Transfer Propulsion Program is summarized in Figure 3. The program consists of propulsion studies, advanced component technology efforts and systems technology activities. Drawing on technology developed in the Orbital Transfer Rocket Engine Technology program, advanced LOX/hydrogen expander cycle engine components will be designed, fabricated and tested in component test stands. The components will then be assembled into a breadboard engine system for proof-of-concept testing. In parallel with these activities, propulsion studies will be conducted to define propulsion system requirements which will guide the selection of focused component technologies to pursue in the program. The advanced engine components emerging from these efforts will be integrated into a focused technology test bed where validation in a simulated environment will complete Level 6 of technology readiness.

# SECTION 4.0

# MANAGEMENT PLAN

## 4.1 OVERVIEW

The Chemical Transfer Propulsion Program is a focused technology program leading to technology demonstrations of an advanced LOX/hydrogen expander cycle engine system and engine components in a technology test bed. The specific objective orientation of the work within the program requires a focused management approach, tailored to the predominant character of the work within the elements of a carefully developed work breakdown structure. Such an approach can ensure achievement of a planned pace of accomplishment, facilitate reporting and permit optimized replanning to achieve the goals and objectives of the program. The work breakdown structure, management structure, program coordination, planning and documentation, reporting and advisory groups for the Chemical Transfer Propulsion Program are described in this section.

## 4.2 WORK BREAKDOWN STRUCTURE

The Chemical Transfer Propulsion Program is divided into three major research areas which allows work to be focused in critical areas and provides a flow mechanism for raising the technology to higher levels of hardware definition, leading to the eventual testing of an advanced LOX/hydrogen engine system in a focused technology test bed in the late 1990's. The major work elements are; 1) Propulsion Studies 2) Mission-Focused Technologies and 3) Engine Systems Technology. Figure 4 illustrates the top-level work breakdown structure elements. The work flows from one element to the succeeding one. The propulsion studies will generate propulsion requirements to guide the selection of mission focused technologies. Advanced engine subcomponents and components emerging from the mission focused technology efforts will be tested in an engine system in the focused technology test bed. The Chemical Transfer Propulsion Project Plan further defines the work breakdown structure to the sub-element level (Ref. 9).

## 4.3 ORGANIZATION AND MANAGEMENT STRUCTURE

Program management responsibilities for the Chemical Transfer

Propulsion Program will reside in OAST's Propulsion, Power and Energy Division, Code RP. A Program Manager in Code RP will be responsible for 1) program planning to establish objectives, scope and overall programmatic approaches 2) providing direction regarding changes and program content to satisfy the objectives of the program and 3) serving as a focal point for NASA Headquarters interests, planning and control of the Chemical Transfer Propulsion Program. The Chemical Transfer Propulsion Program Manager will report on a regular basis to a Program Manager for Pathfinder as to the status, problems and accomplishments of the program. Figure 5 depicts the management structure for the Chemical Transfer Propulsion Program.

The NASA Lewis Research Center (LeRC) will be the Lead Center for the Chemical Transfer Propulsion Program. As the Lead Center, LeRC will assume full responsibility for achieving the goals and objectives of the program, as well as for integrating next-tier assignments in the program both within LeRC and at Participating Centers. LeRC is the only Participating Center in the Chemical Transfer Propulsion Program at the present time. The Marshall Space Flight Center (MSFC) is included in the management structure for the program in Figure 5. MSFC is presently funded by the NASA Office of Space Flight (Code MD) to conduct studies for an advanced space transfer vehicle and may become involved in the program in later stages of technology development. At the present time, only coordination is required to ensure that efforts within the Chemical Transfer Propulsion Program are guided by requirements generated from these vehicle studies.

The Lewis Research Center will plan and integrate Chemical Transfer Propulsion activities and execute some portion of that plan within the Center. A Project Manager located at LeRC will be the focal point of all field installation activity bearing directly on the Chemical Transfer Propulsion Program and will be exclusively responsible for the execution of the program within guidelines and controls prescribed by NASA Headquarters and LeRC management. In essence, the Project Manager will be responsible for the day-to-day supervision and the execution of the program as carried out by industrial contractors, field installation personnel, and university participants. These responsibilities include 1) technical planning 2) maintaining and reporting schedules 3) planning, disbursement and tracking of resources and 4) facility planning as required. Using inputs from all involved organizations, the LeRC will provide a regular, integrated assessment of project status to the Chemical Transfer Propulsion Program Manager.

## 4.4 PROGRAM COORDINATION

The Chemical Transfer Propulsion Program Manager will coordinate closely with personnel in the Office of Exploration (OEXP), Code Z, and the Office of Space Flight (OSF), Code MD, to assure that future space vehicle requirements guide propulsion technology efforts within the Chemical Transfer Propulsion Program. OEXP will define scenarios for future, human exploration missions in the Solar System. OSF will establish space vehicle requirements for these future space exploration missions, which will guide the development of propulsion technologies. Coordination with the Office of Space Science and Applications (Code E) for propulsion requirements for future, unmanned (precursor) Solar System exploration missions will be maintained through Code MD. Mission and vehicle definition (such as requirements for performance, thrust level, throttling, life, reliability and reusability, as well as design criteria for in-space engine operation and maintenance) will be important in establishing technology goals for the Chemical Transfer Propulsion Program. Coordination with OSF will become particularly important in later stages of technology development to facilitate technology transfer and adoption in advanced development programs.

Within OAST, coordination will be maintained with the propulsion R&T Base Program and other Pathfinder elements, as applicable to chemical transfer propulsion technologies. External to OAST, coordination will be maintained with the Department of Defense through the Joint Army, Navy, NASA, Air Force (JANNAF) Interagency Propulsion Committee and the NASA/AF Space Technology Interdependency Group (STIG) for the exchange of information and technology where similar propulsion technologies and applications are in common with NASA's program.

## 4.5 PROGRAM PLANNING AND DOCUMENTATION

A detailed five-year plan, with less detailed planning to ten years, will be developed prior to implementation of the Chemical Transfer Propulsion Program. This plan will be documented in a top-level Program Plan and a detailed Project Plan for the Chemical Transfer Propulsion Program. The Program Plan will be developed by the OAST Chemical Transfer Propulsion Program Manager and will describe the overall goals and objectives, as well as technical, management, resources and facilities plans for the Chemical Transfer Propulsion Program. The Program Plan will serve as a "contract" between the performing OAST discipline division (Code RP) and OAST senior management as to the resource and institutional requirements to achieve the goals and objectives of the program.

The Project Manager at the Lead Center (LeRC) will be responsible for developing a detailed Project Plan for the Chemical Transfer Propulsion Program with guidance from OAST and assistance from organizations participating in the program. The Project Plan will exclusively determine technical content, Center responsibilities, resource allocations, milestones and deliverables for the Chemical Transfer Propulsion Program. It will provide the structure of planned accomplishments which serves to make LeRC accountable for performance, serve as a basis to assess and closely monitor the program by various levels at both LeRC and NASA Headquarters and provide content for essential communication between LeRC and NASA Headquarters. In essence, the Project Plan will serve as a "contract" between LeRC and the OAST Propulsion, Power and Energy Division, Code RP, such that Headquarters is obligated to provide resources while LeRC is required to execute the work to fulfill the stated objectives of the program. The Project Plan will be updated on an annual basis to reflect changes and content as appropriate and will be submitted to NASA Headquarters for approval one month prior to the end of each fiscal year.

The Research and Technology Objectives and Plans (RTOP) will continue to be used as a document in OAST's management system for R&T programs. However, for Pathfinder programs, the Project Plan will serve as a basis for communication and negotiation between Headquarters and the performing Field Center and when approved annually by Headquarters, will become the contract between these organizations. So as to avoid duplication of effort, a brief RTOP that references the Project Plan will be used.

## 4.6 PROGRAM REVIEWS

Formal reviews of the Chemical Transfer Propulsion Program will be conducted semi-annually. A technical review will be held mid-way during the fiscal year, and a programmatic review will be held at the end of each fiscal year.

The focus of the technical review will be program content, status and progress versus the Project Plan. Test results, experimental and analytical data, program accomplishments and progress against the Project Plan will be central to this review. The review will include an advisory committee for the Chemical Transfer Propulsion Program and principal managers and technical specialists directly involved in the program from Headquarters (OAST-RP Program Manager), the Lead Center (the Project Manager and his principal assistants), Participating Centers, contractors and universities. Included in this review will be a special assessment of academe participation in the Chemical Transfer Propulsion Program.

The purpose of the programmatic review near the end of the fiscal year will be for OAST to evaluate the specific Project Plan against schedule, accomplishments and resources. During this formal review, each Participating Center will represent their particular area of expertise and responsibility. The Lead Center will be responsible for making an integrated assessment of progress and accomplishments versus the Project Plan.

Special, detailed technical reviews will also be conducted as necessary to ensure a planned pace of accomplishment to meet the goals and objectives of the program and to expose any problems or potential malfunctions before committing the program to the next step. These special reviews will include;

1) Propulsion trade studies assessment
2) Review of design and analysis methodologies for LOX/hydrogen expander cycle engine components/systems
3) Preliminary and critical design reviews for breadboard engine systems
4) Engine systems technology review (to assess technology prior to initiating focused technology test bed activities)
5) Technology review(s) for mission-focused engine components (prior to their integration into the technology test bed)

In addition, these special reviews may include contractor and in-house research reviews which will be open to NASA program participants. Such special technical reviews will be scheduled and implemented by the Project Manager.

## 4.7 PROGRAM REPORTING

### 4.7.1 MONTHLY REPORTING

Monthly reporting for the Chemical Transfer Propulsion Program will be required on a memorandum basis to the OAST-RP Program Manager. The specific content and format of the monthly report will be determined jointly by the LeRC Project Manager and the OAST-RP Program Manager. Along with this monthly memorandum, the LeRC Project Manager will submit to the OAST-RP Program Manager a set of briefing charts which contain a concise, top-level overview of the program and describe program status, issues and highlights/accomplishments for the reporting month. The OAST-RP Program Manager will, in turn, report monthly on the program to the OAST Program Manager for Pathfinder.

### 4.7.2 QUARTERLY REPORTING

The LeRC Project Manager will be responsible for preparing formal quarterly reports on the Chemical Transfer Propulsion Program for submission to the OAST-RP Program Manager by the middle of the month after the end of business for the preceding quarter. The tentative schedule for the quarterly reports will be;

| | |
|---|---|
| First Quarter (Oct. 1 through Dec. 31) | Jan. 15 Report Due |
| Second Quarter (Jan. 1 through Mar. 31) | April 15 Report Due |
| Third Quarter ( Apr. 1 through June 30) | July 15 Report Due |
| Fourth Quarter (July 1 through Sept 31) | Oct. 15 Report Due |

The Management Information and Control System (MICS) will be the format for the quarterly reports to OAST. This reporting system summarizes technical, managerial, and financial status; problems; and prospects, compared to the Project Plan baseline. Project schedule, progress and resources expended against total allocated resources will be reported for the overall project (and for each Center as other Centers become involved). If Participating Centers (Centers other than LeRC) become involved, each will be responsible for reporting the required information through the Project Manager. Specific control, level of reporting (WBS level), etc. will be determined by the OAST-RP Program Manager and the Pathfinder Program Manager.

### 4.7.3 ANNUAL REPORTING

There will be no formal requirement for a separate annual report for the Chemical Transfer Propulsion Program. However, one of the four quarterly reports for each year will be augmented (per future instructions) to provide an annual report as well as a report for that quarter. This annual report will be provided to the OAST-RP Program Manager by the LeRC Project Manager.

### 4.7.4 SPECIAL REPORTS

The LeRC Project Manager will provide for the appropriate distribution of special technical reports, plans and materials documenting contractor, university and in-house research efforts conducted in the Chemical Transfer Propulsion Program. Distribution will include, as appropriate, principal managers and technical specialists directly involved in the program from Headquarters (OAST-RP Program Manager), Participating Centers, contractors and universities, as well as personnel from other NASA Headquarters Program Offices and other Government agencies where similar propulsion technologies and applications are in common with OAST's program.

Informal telecons and face-to-face meetings and visits (as necessary) between the program and project management for the Chemical Transfer Propulsion Program will also be conducted to communicate data, problems and recommendations in a timely fashion.

### 4.8 ADVISORY COMMITTEES

The OAST Space Systems Technology Advisory Committee (SSTAC) structure and advisory mechanisms will be utilized for the Chemical Transfer Propulsion Program. At minimum, this advisory group will provide top-level programmatic and technical guidance to the program in a meeting early each fiscal year. In addition, a Space Propulsion Advisory Committee may be assembled to provide a more dedicated and specific advisory function for the Chemical Transfer Propulsion Program. This committee will be composed of principal managers and technical specialists from NASA, other government agencies, industry and academe and will provide specialized oversight as to the planning, execution and monitoring of progress in the Chemical Transfer Propulsion Program. At minimum, this committee will furnish specific programmatic and technical guidance to the program once each year at the mid-fiscal year technical review. The LeRC Project Manager will propose, assemble and determine the specific charter of the Space Propulsion Advisory Committee.

# SECTION 5.0

# TECHNICAL PLAN

## 5.1 TECHNICAL OVERVIEW

The Chemical Transfer Propulsion Program will evolve fundamental LOX/hydrogen expander cycle propulsion technologies through component, subsystem and system technology hardware demonstrations. Work in the Base R&T program over the past several years has been directed toward establishing subcomponent and component technologies capable of meeting expected mission requirements and pursuing critical technological advances necessary for those engine concepts to achieve performance, life and operational goals. Advanced design concepts and analytical methods have been developed using laboratory and specially designed test equipment to generate a data base for design verification and code validation.

The Chemical Transfer Propulsion Program will build on the R&T Base results by moving progressively through full scale component, subsystem, and system level validation and demonstration programs. The program will consist of three phases. Phase I will be directed toward component level advanced design and computer code development and validation. Highly instrumented engine components capable of operating over a wide range of conditions will be designed, fabricated and tested for code validation and refinement. Full scale point design hardware will be fabricated and tested to demonstrate technology readiness of component and subsystem design and analysis tools. This phase of the program will be completed in fiscal year 1992. In Phase II the demonstrated components and subsystems from Phase I will be assembled and integrated into an engine system to conduct component interaction and system level validation testing. Engine models to predict transient, steady state and throttling performance will be developed, validated and refined. The output of this phase of the program will be the validation of high pressure LOX/hydrogen expander cycle engine design concepts. Phase II will be completed in fiscal year 1994. The third phase of the program will be directed toward demonstrating the performance, life and operation of a LOX/hydrogen expander cycle engine system designed to meet the requirements of space transfer and lander vehicles for future space exploration missions. As a goal, the engine will have capability for automated preflight operations and fault-tolerant flight operations and incorporate design criteria for in-space operation and maintenance. When this phase of the program is complete (circa 1998) the hardware will be available to be used as a test bed for problem solving and for product improvement activities.

Propulsion studies, mission focused technology efforts, and engine system technology efforts will be conducted, leading to the eventual testing of a high performance LOX/hydrogen expander cycle engine system and advanced engine components in a focused technology test bed. The objectives and overall technical approach for each of these three work breakdown structure areas are described briefly in the following sections.

### 5.1.1 PROPULSION STUDIES

The objectives of the Propulsion studies are to provide engine parametric data to support ongoing mission/vehicle studies and to optimize engine components and systems to satisfy the propulsion system requirements resulting from these studies. Study results will guide subcomponent and component efforts to be conducted in the Mission-Focused Technologies area.

### 5.1.2 MISSION-FOCUSED TECHNOLOGIES

The objective of Mission-Focused Technology efforts will be to formulate concepts and demonstrate subcomponent and component technologies for an advanced LOX/hydrogen expander cycle engine. Propulsion requirements for throttling, life, reusability, performance, and in-space operation and maintenance will drive the selection of technologies to be pursued in this area. Advanced design concepts and analytical methods will be developed and proof-of-concept will be demonstrated utilizing laboratory, bench and rig testing. In promising technical areas, these advanced design concepts and analytical methods will be used to design and fabricate component and subsystem hardware for performance validation tests. Validated components and analytical methods will then be made available for incorporation into the focused technology test bed.

### 5.1.3 ENGINE SYSTEMS TECHNOLOGY

The objectives of the Engine Systems Technology efforts are;

1) Validation of the high pressure, high performance expander cycle engine concept
2) Investigation of system interactions, transients, dynamics, control functions and preliminary health monitoring techniques
3) Systems testing of advanced technology engine components, control

systems, and health monitoring/diagnostic systems

4) Verification of component and system design/analysis computer simulation (codes)

5) Demonstration of mission-focused LOX/hydrogen expander cycle engine component and systems technologies in a technology test bed.

The proof-of-concept of an advanced LOX/hydrogen expander cycle engine will be accomplished by the validation testing of a breadboard engine. After thorough testing of the breadboard engine, demonstrated mission-focused components emerging from Mission-Focused Technology efforts will be integrated to comprise a mission-focused test bed engine. This test bed engine will be tested to validate and demonstrate, in a simulated environment, its capability to satisfy the propulsion requirements for future space exploration missions.

## 5.2 SUMMARY OF DELIVERABLES

For Pathfinder, 1992 is considered a point in time when assessment of technology status will occur (Ref. 10). 1992 is considered the earliest probable time in the near future when a National decision and commitment may be made regarding further exploration of the Solar System. For missions occurring early in the twenty-first century, development programs must be initiated late in the 1990's (circa 1998). Therefore, it is important to quantify and plan for deliverables from Pathfinder Programs for both 1992 and 1998; with 1992 being a "window of knowledge" when an assessment of technology status will occur and 1998 being a time of technological readiness to confidently proceed with development of programs in relevant areas. In this Section 1992 deliverables, 1998 deliverables and technology readiness objectives for the Chemical Transfer Propulsion Program are specified.

### 5.2.1 1992 DELIVERABLES

By the end of 1992 engine parametric data packages and propulsion trade studies will be complete. Propulsion system requirements to guide technology efforts in the program will be defined from mission, vehicle and propulsion studies. Technology concepts and applications for advanced, mission-focused engine subcomponents and components will be formulated. Proof-of-concept of many of these advanced design concepts and analytical methods will be demonstrated using laboratory bench and rig tests. Design criteria for in-space engine operation and maintenance will be defined leading to programs directed at health monitoring and control systems, fault-tolerant engine operations, and automated preflight checkout, as well as design criteria for in-space change-out. Breadboard engine efforts leading to validation of the high pressure/high performance LOX/hydrogen expander cycle engine concept will be well underway. Design methodologies and analytical models will be assembled and computer simulations conducted to design engine hardware and predict engine component and system performance. Testing of components for the breadboard engines will be nearly complete leading to validation of engine component design methodologies and analysis models.

### 5.2.2 1998 DELIVERABLES

By 1998 all critical technologies for an advanced LOX/hydrogen expander cycle engine will be developed and verified in a focused technology test bed. The proof-of-concept of an advanced, high performance LOX/hydrogen expander cycle engine will be a result of breadboard engine tests. Included in these tests will be investigations of system interactions, transients, dynamics, control functions and health monitoring techniques, as well as testing of advanced engine components. Verification of component and system design/analysis computer codes will be completed. A focused technology test bed will be assembled by integrating components from Mission-Focused Technology efforts. Test bed engine testing in a simulated environment will validate a system design and analysis technology base and design concepts for a high performance, space-based, throttleable LOX/hydrogen expander cycle engine, including definition of health monitoring and control systems and design criteria for operation and maintenance of the engine in space. By 1998 the technology necessary to confidently proceed (in terms of technical, cost, and schedule risk) with the development of an advanced, high performance LOX/hydrogen expander cycle engine to meet future space exploration mission requirements will be available.

### 5.2.3 TECHNOLOGY READINESS OBJECTIVES

The technology readiness level of LOX/hydrogen expander cycle propulsion systems for chemical transfer as the Chemical Transfer Propulsion Program is initiated in fiscal year 1989 in support of future space exploration missions can be considered Level 3, as shown in Table III. Key LOX/hydrogen expander cycle engine components (such as pumps, turbines, thrust chambers and health monitoring devices) and related component analytical models have been designed, fabricated and tested for proof-of-concept in the Base R&T program over the past several years. With this as a starting point, the Chemical Transfer Propulsion Program will design, fabricate and test advanced components based on these proof-of-concept designs. These advanced components will be tested in component test stands to determine expected performance and validate component analysis models and design methodologies to elevate technology readiness to Level 4. The components will then be integrated into a breadboard engine for system proof-of-concept testing and system-level investigations. Advanced engine components emerging from Mission-Focused Technology efforts will be integrated and tested in a focused technology test bed to elevate technology readiness to Level 5. System validation of hardware and analysis concepts will be conducted in the focused technology test bed in a simulated space environment to complete Level 6 of technology readiness. At this point in the program, in the late 1990's, the goals and objectives of the Chemical Transfer Propulsion Program will be met. Validated hardware and design methodologies/analysis models may then be transferred to the development program.

## 5.3 SCHEDULE AND MILESTONES

Primary tasks and major milestones/deliverables through fiscal year 1998 for the Chemical Transfer Propulsion Program are provided in Table IV. Adherence to the proposed schedule and attainment of the milestones is contingent upon the approved funding as provided in Section 6.1. More specific schedules for the conduct of the technology tasks are provided in the Chemical Transfer Propulsion Project Plan.

## SECTION 6.0

## RESOURCES AND FINANCIAL MANAGEMENT PLAN

### 6.1 FIVE YEAR FUNDING REQUIREMENTS

Projected funding requirements to accomplish the milestones and to provide deliverables as noted in Section 5.0 for the Chemical Transfer Propulsion Program for fiscal years 1989 through 1993 are approximately $76 million. Pathfinder funding approved and allocated to the Chemical Transfer Propulsion Program for fiscal year 1989 totals $4.0 million. Funding requirements for the first five years of the Chemical Transfer Propulsion Program are summarized in Table V.

### 6.2 FIVE YEAR WORKFORCE REQUIREMENTS

Table V provides the estimated Civil Service personnel requirements for the first five years of the Chemical Transfer Propulsion Program. Support service contractor personnel required to augment civil servant resources are not included in these estimates.

### 6.3 LONG RANGE RESOURCE REQUIREMENTS

Current plans place the focused technology test bed for the Chemical Transfer Propulsion Program at a Government test facility. Efforts to assemble the test bed would begin in fiscal year 1994, so the workforce requirements for this activity are not reflected in Table V. In fiscal year 1989 the Lead Center for the Chemical Transfer Propulsion Program will prepare (specific content per future instructions) an Institutional Resources Assessment for the program which will address (civil servant and on-site support contractor) workforce (and facility) requirements and recommend a site to conduct a focused technology test bed test program using Government personnel and facilities. This assessment will be submitted to the OAST-RP Program Manager for approval by the end of fiscal year 1989.

### 6.4 CONTRACTING PLANS

Contracted efforts in support of the Chemical Transfer Propulsion Program will include industry and universities, as appropriate, (as well as potential involvement through the Small Business Innovative Research (SBIR) Program to provide needed capabilities not within the current or planned future expertise of the agency. Efforts provided under contract to NASA will include such services as research and technology development tasks in specific areas defined by NASA, support service contractors of a technical or administrative nature, and other services as appropriate.

### 6.4.1 INDUSTRY

The expertise of the aerospace industry will be extensively utilized in each of the three work breakdown structure elements of the Chemical Transfer Propulsion Program. Industry will participate in the Propulsion Studies to provide engine parametric data which will supply definition for future technology efforts within the program. A number of contracts with industry will be initiated in the Mission-Focused Technologies area, addressing various advanced technologies for LOX/hydrogen expander cycle engines. Industry will have a strong role in formulating concepts as a basis for technology programs in this area. In the Engine Systems Technology area, industry will be involved in the design, fabrication and (checkout) testing of breadboard hardware and relevant design methodologies and analytical models for an advanced LOX/hydrogen expander cycle rocket engine. At the Governments option, industry may conduct test programs with the breadboard hardware at industrial facilities.

### 6.4.2 ACADEME

Another means of accomplishing (basic) research and technology in support of the Chemical Transfer Propulsion Program is through the use of university grants in areas which have been proposed by the academic community and which may have potential benefit to advanced LOX/hydrogen expander cycle propulsion systems. Academe will be encouraged to participate in the Chemical Transfer Propulsion Program, particularly in the Mission-Focused Technologies area to formulate concepts as a basis for advanced technology programs and to conduct basic research in support of the Chemical Transfer Propulsion Program. Mechanisms to promote academe participation in the Chemical Transfer Propulsion Program may be provided at the Center or OAST management level. The University Space Research Engineering Program is a mechanism for OAST management to promote academe participation. (In fiscal year 1988, Pennsylvania State University was named the Center for Space Propulsion Engineering and the University of Cincinnati was named Health Monitoring Technology Center for Space Propulsion Systems.) Regular review of NASA-funded academic activities in support of the Chemical Transfer Propulsion Program will be held to highlight academic research and promote a free exchange of technology ideas among the propulsion community.

# SECTION 7.0

# FACILITIES PLAN

## 7.1 FACILITIES ASSESSMENT

Some modifications and/or reactivation of existing facilities may be required for the Chemical Transfer Propulsion Program, but no new facilities are envisioned at this time.

## 7.2 LABORATORIES AND COMPUTING

Existing laboratories and computing facilities should be adequate to support the Chemical Transfer Propulsion Program through 1994, where the primary emphasis of research will be on validation of engine component design concepts, design methodologies and analytical models. State-of-the-art computing facilities within NASA and industry should prove sufficient for computer simulations which will be developed and used for LOX/hydrogen expander cycle engine subcomponents, components and systems.

## 7.3 DEMONSTRATION FACILITIES AND TESTING

Current plans place the breadboard engine test bed (late in fiscal year 1992) and the focused technology test bed (early in fiscal year 1995) for the Chemical Transfer Propulsion Program at Government test facilities. Demonstration testing of the focused technology test bed engine may include deep throttling and a large area ratio nozzle. Testing of such hardware in a simulated space environment will require a specialized vacuum exhaust rocket engine test stand. Several Government test facilities have the required capability, however it is not clear at this time which Government facility is best suited for the technology test bed and whether institutional constraints will permit these test programs to be conducted at Government facilities. Therefore, a facilities assessment will be included in the Institutional Resources Assessment to be prepared by LeRC for the Chemical Transfer Propulsion Program in fiscal year 1989. This assessment will include demands on existing propulsion test facilities in order to support the Chemical Transfer Propulsion Program. Consistent with near and far term research and technology development goals, the adequacy and availability of existing facilities will be assessed for the conduct of test bed engine test programs with Government facilities (and personnel). If the test bed requires construction of facilities (CoF) support, it will be vitally important to have the facility defined, planned and included in the CoF funding cycle for construction beginning in the early 1990's. Identifying the requirements for, and planning for such facility capability will be the responsibility of the Chemical Transfer Propulsion Project Manager. Advocacy within OAST for proposed chemical transfer propulsion facility capability will be the responsibility of the OAST-RP Program Manager with support from the Project Manager, as appropriate.

# SECTION 8.0

## TECHNOLOGY TRANSFER PLAN

The effective transfer of propulsion technologies from the research Center to the development Center where the technology will eventually be developed into operational systems for future space exploration missions is recognized as a major goal of the Chemical Transfer Propulsion Program. Planning for the transition of Chemical Transfer Propulsion focused technology to advanced development in preparation for implementation involves both Headquarters and the Field Centers.

At Headquarters, it is critical that the OAST-RP Program Manager develop a constructive, collaborative and supportive relationship with the Advanced Program Development organization (Code MD) such that they may shape the technology program content, monitor progress and facilitate transfer and adoption of technology from the program. The Program Plan and Project Plan for the Chemical Transfer Propulsion Program will be transmitted to Code MD to coordinate with them relative to the content of the program. In addition, the OAST-RP Program Manager will allow for ongoing insight into technology development in the Chemical Transfer Propulsion Program through Code MD participation in meetings and briefings, as appropriate. The OAST-RP Program Manager will also be responsible to remain cognizant of Code MD programs and activities as they pertain to the Chemical Transfer Propulsion Program.

In addition, it is vital to provide for development Center participation in the Chemical Transfer Propulsion Program in later stages of technology development. This is a primary reason for including the Marshall Space Flight Center in the program management structure for the Chemical Transfer Propulsion Program (Figure 5). Either the Lewis Research Center or the Marshall Space Flight Center would be the developer of an advanced LOX/hydrogen expander cycle engine for future space exploration missions. In fiscal year 1989 the LeRC Project Manager will be responsible for developing and submitting to the OAST-RP Program Manager a formal Technology Transfer Plan which will identify mechanisms for the implementation of technology transfer within NASA and among industry, universities and other Government agencies, as appropriate.

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4. **Project Pathfinder: Research and Technology to Enable Future Space Missions.** OAST; (Washington, D.C: Brochure/JPL 400-330). December 1987.

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9. **Chemical Transfer Propulsion Project Plan.** NASA Lewis Research Center. Cleveland, Ohio. 1988.

10. **Report of the OAST Task Force on Focused Program Management for Dr. William F. Ballhaus, Jr.**; (Unpublished). May 11, 1988.

# FIGURES

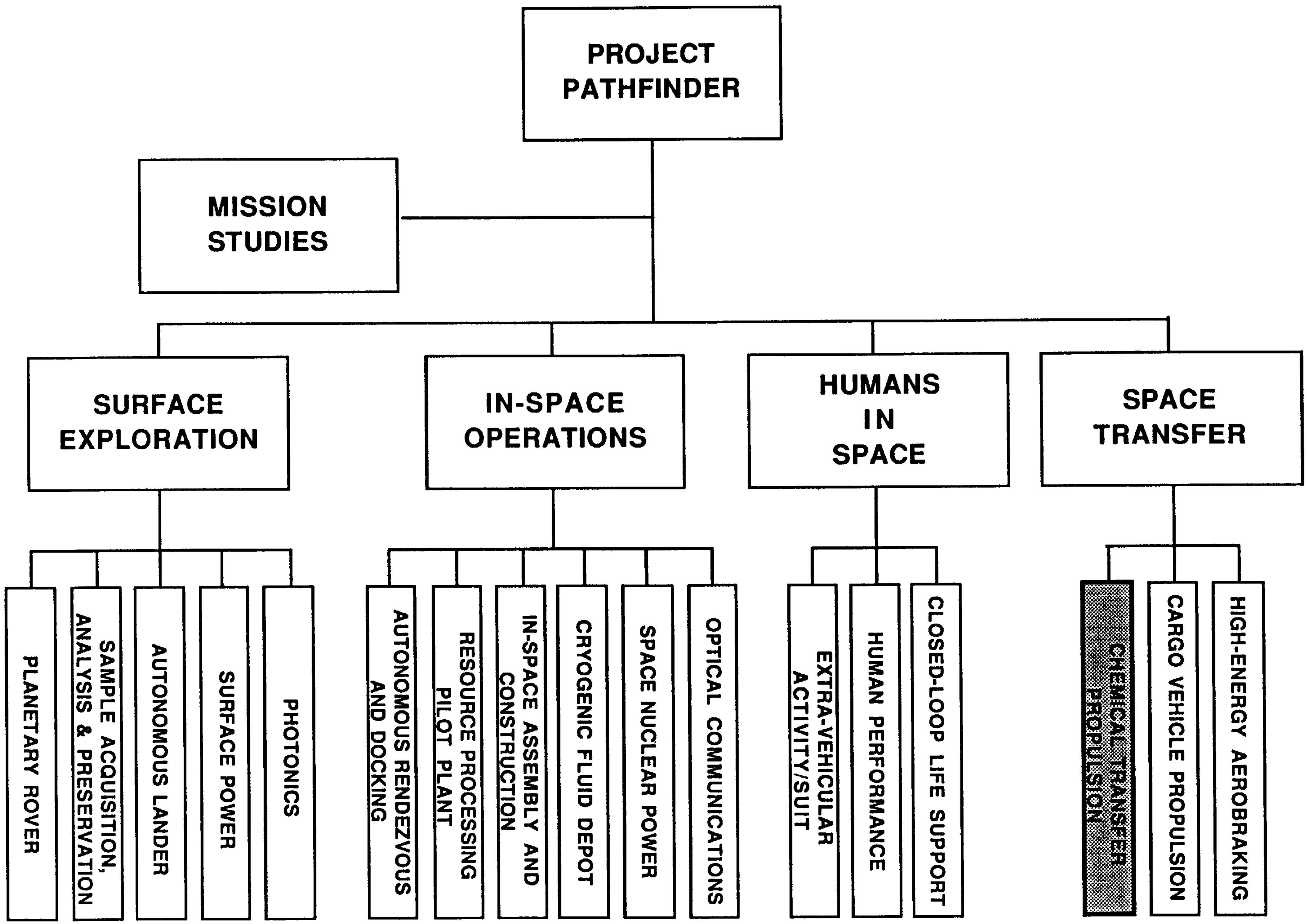
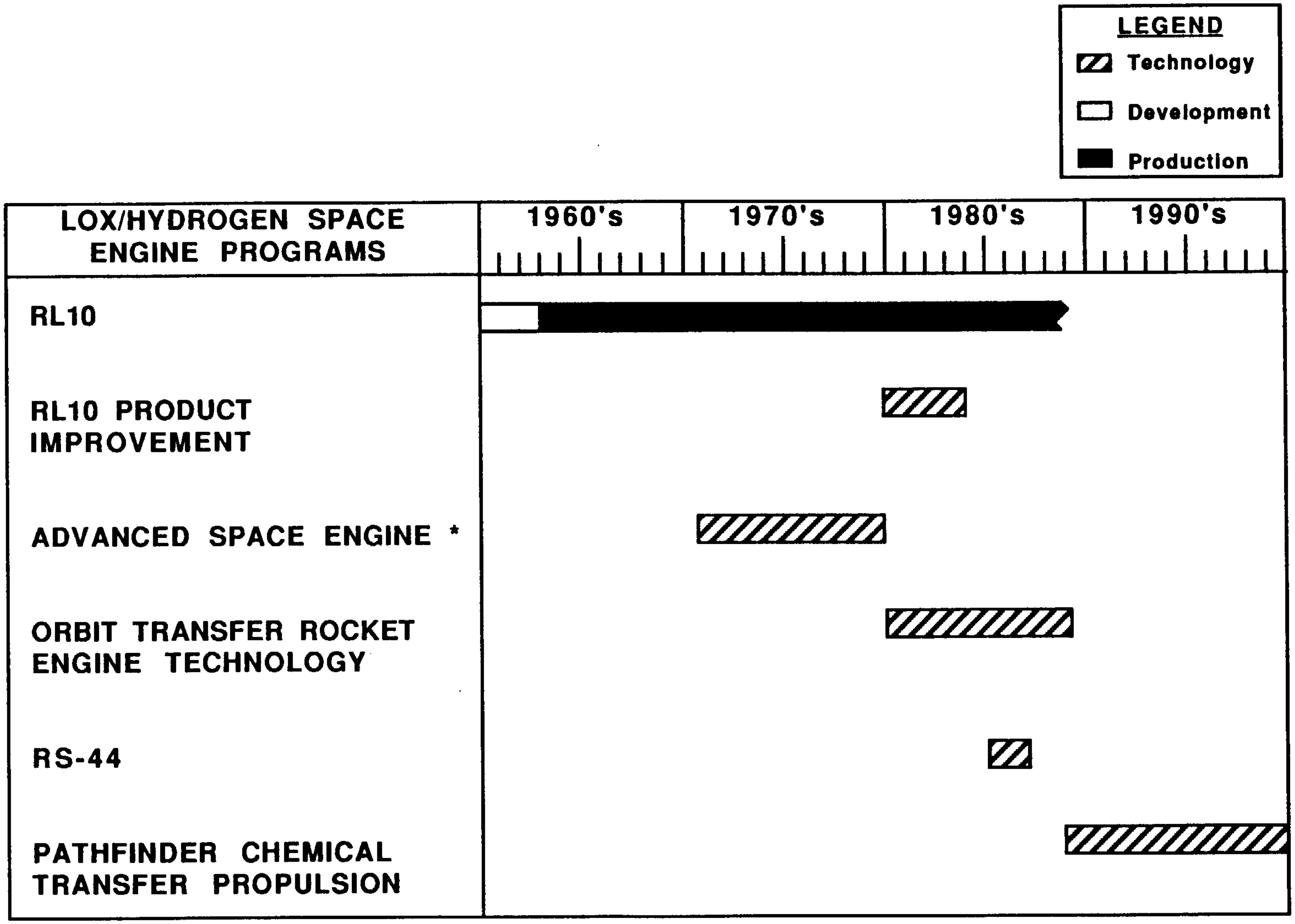



Figure 1: Project Pathfinder Work Breakdown Structure




* Staged Combustion Cycle

Figure 2: LOX/Hydrogen Upper Stage Engine History

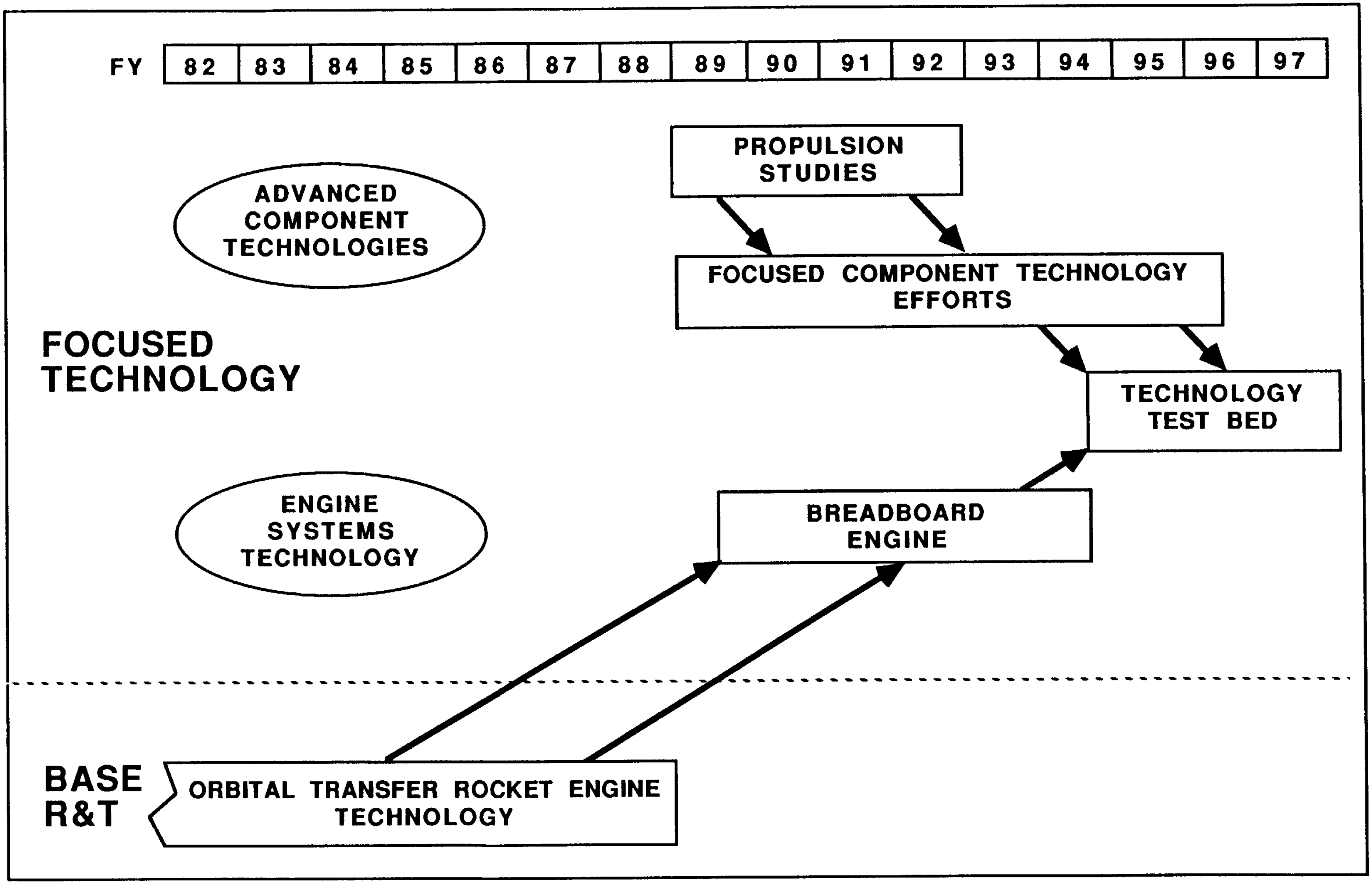



**Figure 3: Chemical Transfer Propulsion Technical Approach**

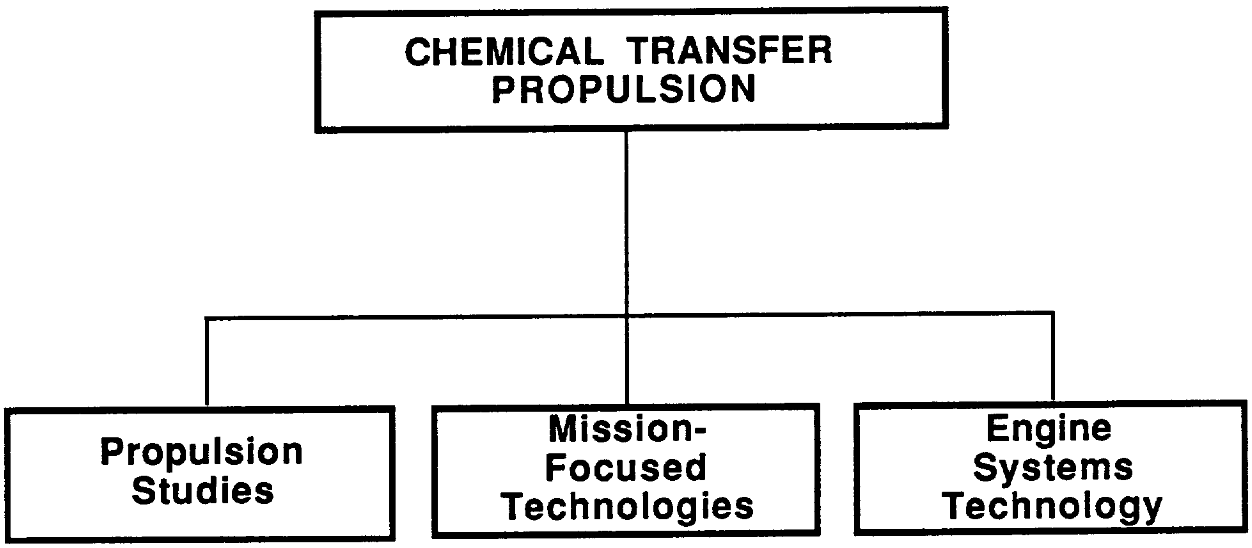



Figure 4: Work Breakdown Structure for Chemical Transfer Propulsion Program

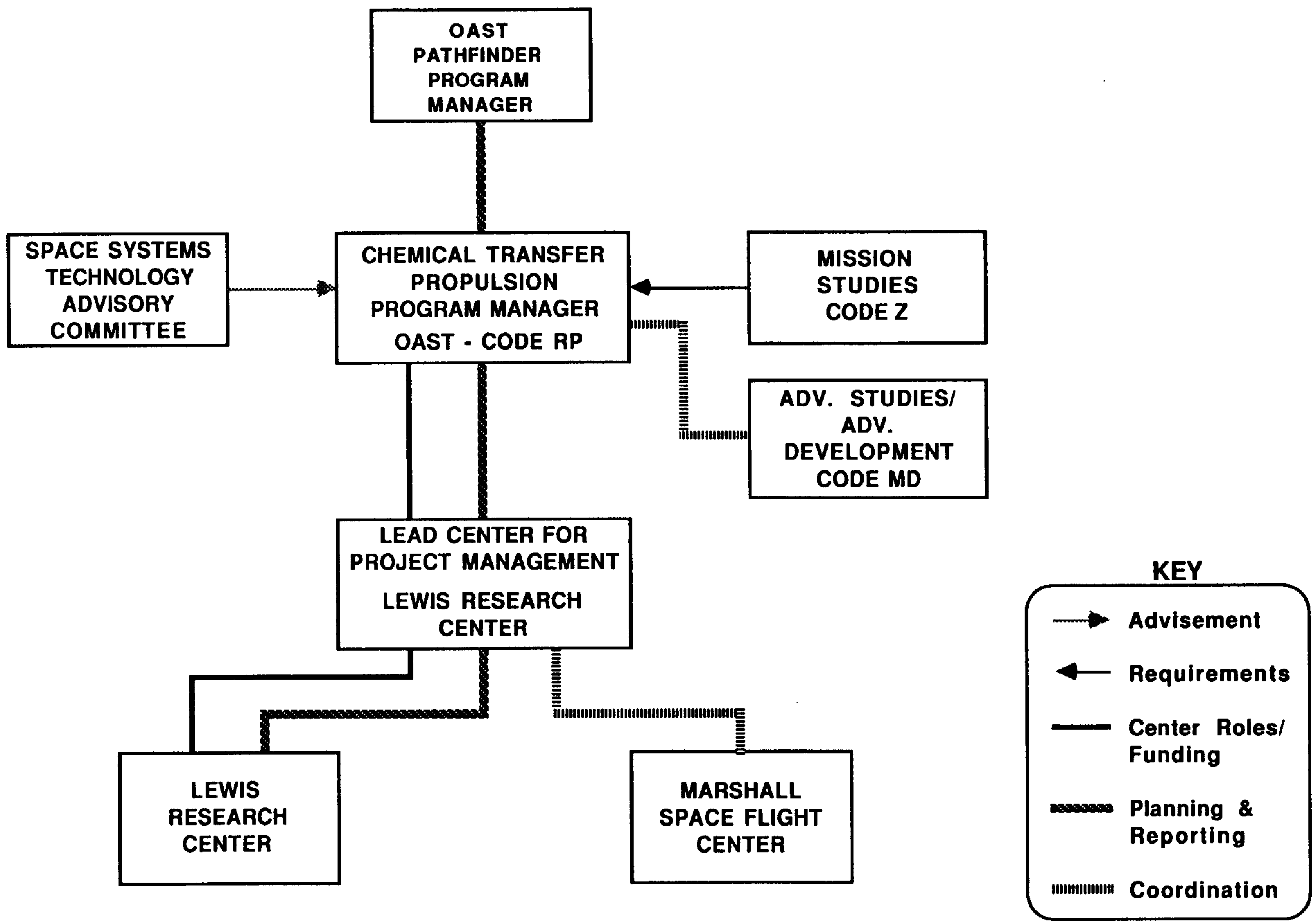



Figure 5: Chemical Transfer Propulsion Management Structure

# TABLES

| MISSION | THRUST | FUEL | ISP (SEC) | BURN TIME | REUSE | THROTTLEABLE | SPACE EXPOSURE |
|---|---|---|---|---|---|---|---|
| Mars Transfer (1st & 2nd stage) | 75-100 K | LOX/LH2 | > 460 | < 30 min | Yes (10) | No | Months |
| Lunar Transfer<br>Mars Transfer (3rd stage)<br>Mars/Lunar Return | 20-40 K | LOX/LH2 | > 480 | 45-90 min | Yes (10) | No | Years |
| Mars and Moon Descent | 20-40 K | LOX/LH2 | > 450 | 10-20 min | Mars-No<br>Moon-Yes | Yes | Years |
| Mars and Moon Ascent | 20-40 K | Note 1 | Max | < 20 min | Mars-No<br>Moon-Yes (10) | No | Years |

Note 1: Must be compatible with surface heat loads and stay times to reduce propellant losses to mission acceptable levels

Table I: Chemical Transfer Propulsion Technology Requirements

| Parameter | | Reference Engine System (RL-10A-3-3A) | Space Transfer Vehicle Engine Technology Goals |
|---|---|---|---|
| Propellants - | Fuel | Hydrogen | Hydrogen |
| | Oxidizer | Oxygen | Oxygen |
| Power Cycle | | Expander | Expander |
| Vacuum Thrust | | 16,500 lbf* | 5 to 50 Klbf (Note 1) |
| Vacuum Thrust Throttling Ratio | | Not Specified | 20:1 (Note 2) |
| Vacuum Specific Impulse | | 444.4 lbf-sec/lbm | > 490 lbf-sec/lbm |
| Engine Mixture Ratio, O/F | | 5.0* | 6.0 (Note 3) |
| Engine Mixture Ratio Range | | 4.4 to 5.6 | 5.0 to TBD (Note 4) |
| Combustion Pressure | | 465 psia* | > 1500 psia (Note 5) |
| Nozzle Area Ratio | | 61:1 | 1000:1 |
| Weight | | 310 lbs | TBD |
| Length | | 70.1 in. | TBD |
| Life - | Operational | 3 starts, 4000 sec. | > 500 starts, 20 hours |
| | Service Free | Not Specified | > 100 starts, 4 hours |
| Basing | | Earth | Space |
| Human Rating | | No | Yes |
| Design Criteria - | Operational | Not Specified | Fault Tolerance |
| | Aerobrake | None | Compatible with Aeroassist Transfer |
| | Maintenance | Not Specified | In-Space Maintenance |
| | Diagnostic Instrumentation | None | Integrated Controls and Health Monitoring |

* - Design Point
TBD - To Be Determined
Note 1 - Thrust goal to be determined. Expected to be in 5,000 to 50,000 lbf thrust range.
Note 2 - Continuous and stable throttling from rated thrust to 5% thrust with minimum performance loss.
Note 3 - Mixture ratio goal to be determined. Performance goal specified at a mixture ratio of 6.0.
Note 4 - Engine mixture ratio range to be determined. Broad range desired for compatibility with fault tolerant engine operation and to potentially allow mixture ratio change during mission.
Note 5 - Chamber pressure must be compatible with performance and throttling goals.

Table II: Technology Goals for Space Transfer Engine

*BASIC RESEARCH*

*FEASIBILITY RESEARCH*

*TECHNOLOGY DEVELOPMENT*

*TECHNOLOGY DEMONSTRATION*

| | |
|---|---|
| <u>LEVEL 1</u> | BASIC PRINCIPLES OBSERVED & REPORTED |
| <u>LEVEL 2</u> | TECHNOLOGY CONCEPT/APPLICATION FORMULATED |
| <u>LEVEL 3</u> | ANALYTICAL AND EXPERIMENTAL CRITICAL FUNCTION AND/OR CHARACTERISTIC PROOF-OF-CONCEPT |
| <u>LEVEL 4</u> | COMPONENT AND/OR BREADBOARD VALIDATION IN LABORATORY |
| <u>LEVEL 5</u> | COMPONENT AND/OR BREADBOARD DEMONSTRATION IN RELEVENT ENVIRONMENT |
| <u>LEVEL 6</u> | SYSTEM VALIDATION MODEL DEMONSTRATED IN SIMULATED ENVIRONMENT |
| <u>LEVEL 7</u> | SYSTEM VALIDATION MODEL DEMONSTRATED IN SPACE |

**TABLE III: Technology Readiness Levels**

| | FY 89 | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 |
|---|---|---|---|---|---|---|---|---|---|---|
| **PROPULSION STUDIES** | | | | | | | | | | |
| • Engine Parametric Data Packages | | Δ | | | | | | | | |
| • Propulsion Trade Studies Complete | | | | Δ | | | | | | |
| • Propulsion System Requirements | | | | Δ | | | | | | |
| **MISSION-FOCUSED TECHNOLOGIES** | | | | | | | | | | |
| • Technology Concepts/Applications Formulated | | Δ | | | | | | | | |
| • Component Technology Concept Demonstrated | | | Δ | Δ | Δ | | | | | |
| • Engine Component Validations in Test Bed Engine | | | | | | | Δ | Δ | Δ | |
| • Health Monitoring and Control Systems Defined | | | | | | | | Δ | | |
| • Component Design/Analysis Methodologies Verified | | | | | | | | | Δ | |
| **ENGINE SYSTEMS TECHNOLOGY** | | | | | | | | | | |
| • Breadboard Engine Contracts Initiated | Δ | | | | | | | | | |
| • Design/Analysis Methodologies Assembled | | Δ | | | | | | | | |
| • Critical Design Reviews for | | Δ | | | | | | | | |
| • Breadboard Engines | | | | | | | | | | |
| • Breadboard Component Tests Complete | | | | Δ | | | | | | |
| • Component Codes Validated | | | | Δ | | | | | | |
| • Breadboard Engine Tests Complete | | | | | | Δ | | | | |
| • Focused Technology Test Bed Engine Assembled | | | | | | | | | Δ | |
| • Validated System Design/Analysis Technology Base | | | | | | | | | | Δ |

Table IV: Chemical Transfer Propulsion Program Milestones/Deliverables

| RESOURCES | SCHEDULE (FISCAL YEARS) | | | | |
|---|---|---|---|---|---|
| | 1989 | 1990 | 1991 | 1992 | 1993 |
| FUNDING ($,M) | 4.0 | 10.0 | 22.0 | 22.0 | 18.0 |
| NASA WORKFORCE (WY/Y) | 27 | 40.5 | 41 | 41 | 45 |

Table V: Chemical Transfer Propulsion Projected Resources